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EFFECTS OF LOAD DISTRIBUTIONS AND AXLE AND TIRE CONFIGURATIONS ON PAVEMENT FATIGUE

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EFFECTS OF LOAD DISTRIBUTIONS AND AXLE AND TIRE CONFIGURATIONS ON PAVEMENT FATIGUE

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ABSTRACT

Damage factor relationships for axle and tire configurations are presented. Adjustment factors are provided to account for variations in load distributions within axle groups, distances between axles of a tandem, and variations in tire pressure for both dual and flotation tires.

Properly accounting for accumulated fatigue of a pavement requires a reasonable measure of traffic volume, proportions of vehicle styles (classifications) within the traffic stream, dates of service, estimate of the average damage factor for each classification, and estimates of tire contact pressures.

All adjustment factors presented are based on analyses of a limited number of structures and should be used with caution. The accuracy of these analyses is not in question, but the range of structures investigated was limited. They are intended to indicate the trend, shape, and sensitivity of various inter-relationships and their relative magnitudes. Modifications may have to be made upon the analyses of additional pavement structures. Kentucky traffic may differ from that in other areas, both in types of vehicles in the traffic stream and the type and direction that cargo is being transported.

INTRODUCTION

Flexible pavement designs are primarily a function of traffic volume, material characteristics, and the relative damage caused by various axleloads and their configurations. If material characteristics and traffic volume are assumed to have been determined, variations in thicknesses would be a function of relative damage factors, i.e., the loading conditions. Analyses of traffic loading presented in this paper are predicated upon the concept of strain energy density (1) exerted by the pavement to resist the loadings. Strain energy is work done internally by the body and is equal to and opposite in direction to work done upon the body by an external force. Strain energy is the integral of strain energy density. The Chevron N-layer (2) program was modified to perform the strain energy density calculations for specified depths and radial distances from the center of the load.

ANALYSES OF AXLE CONFIGURATIONS

Uniform Loading

The Chevron N-layer computer program was used to analyze the effects on highway pavement performance of tire and axle configurations where all tires in a configuration were equally loaded. The load for each individual tire in each axle configuration was varied from 2 kips (8.9 kN) to 8 kips (35.6 kN) on 0.5-kip (2.2-kN) increments. At the AASHO Road Test, there were 100 possible combinations of layer thicknesses, of which 67 were constructed. All 100 possible combinations of layer thicknesses were used in the computer analyses to obtain relationships between damage factor and total load on various axle configurations. Thicknesses of asphaltic concrete ranged from 2 inches (51 mm) to 6 inches (152 mm) on 1-inch (25-mm) increments. Base thicknesses ranged from 0 to 9 inches (0 to 229 mm) on 3-inch (76-mm) increments, and subbase thicknesses ranged from 0 to 16 inches (0 to 406 mm) on 4-inch (102-mm) increments. An 18-kip (80-kN) four-tired single axleload was applied to each of the 100 structures as the reference condition.

The load equivalency (damage) factor is defined by

$$DF = N18 \,/\, NL, \qquad 1$$

in which DF = damage factor,

N18 = repetitions for which the work strain is that due to an 18-kip (80-kN) four-tired single axleload, and

NL = repetitions for which the work strain is that due to the total load on the axle or group of axles.

Figure 1 shows the relationships between damage factor and total load on axle groups when the load is uniformly distributed amongst the axles of the group. The curves shown in Figure 1 may be approximated by

$$\log(DF) = a + b(\log(Load)) + c(\log(Load))^2, \qquad 2$$

in which DF = damage factor of total load on axle configuration relative to an 18-kip (80-kN) four-tired axleload,

Load = axleload in kips, and

a, b, c = regression coefficients (Table 1(3)).

Uneven Loads on Tandems

The effects of uneven load distributions on the axles of a 36-kip (160-kN) tandem group were investigated using a number of different structures. Analyses revealed that the damage factor for the load distributed evenly on the 36-kip (160-kN) tandem should be adjusted by a multiplying factor (MF) illustrated in Figure 2 (3) to account for uneven load distributions. To obtain a "feel" for the impact of such unequal load distributions, the first 670 tandem axleload

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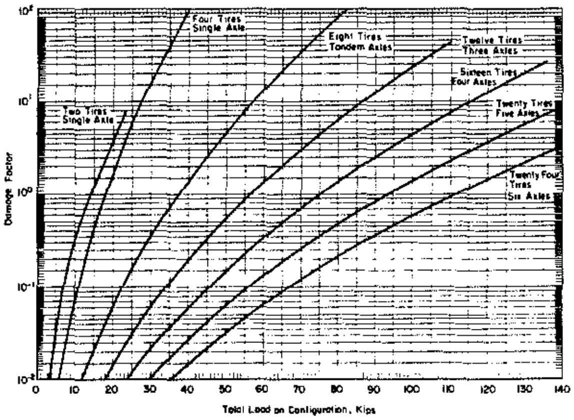

Figure 1. Relationship between Load Equivalency and Total Load on the Axle Group, Evenly Distributed on All Axles.

distributions listed in the 1980 W-4 tables for Kentucky were analyzed. A 40-percent increase in the calculated fatigue resulted when the uneven load distribution was considered.

Uneven Loads on Tridems

The increased use of tridem axle groups suggested an investigation of actual load distributions. Inspection of the W-4 table revealed that the majority of tridems had uneven load distributions. Adjustment factors to account for those uneven loadings were developed. The structures used to analyze effects of uneven loads on tandems were used. The total load was kept constant at 54 kips (240 kN). Five basic patterns of load distributions were investigated. Considering patterns that were mirror images

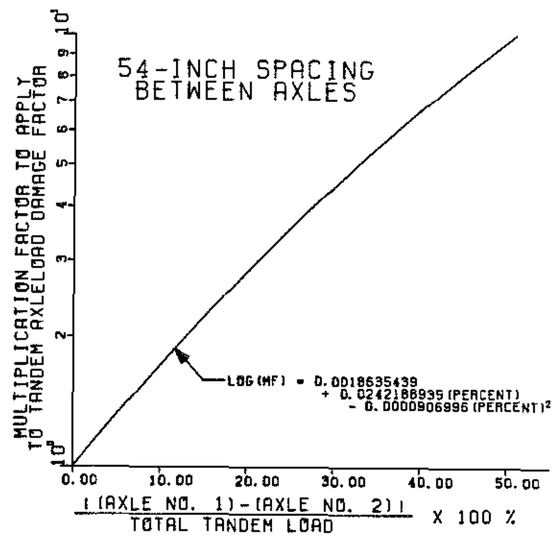

Figure 2. Multiplying Factor to Account for Uneven Load Distribution on the Two Axles of a Tandem.

of one of the five and that two of the axles might be equally loaded, there were 13 combinations. The following definitions were used:

- M = the heaviest axleload of the three axles,
- L = the least axleload of the three axles,
- I = the intermediate axleload between the maximum and minimum axleloads, and
- E = the axleload is equal to an axleload on at least one other axle.

The allowable repetitions associated with 54 kips (240 kN) uniformly distributed on the

TABLE 1. REGRESSION COEFFICIENTS TO CALCULATE DAMAGE FACTORS FOR VARIOUS AXLE CONFIGURATIONS

$$\log(\text{Damage Factor}) = a + b(\log(\text{Load})) + c(\log(\text{Load}))^2$$

AXLE CONFIGURATION	COEFFICIENTS a	b	c
Two-Tired Single Front Axle	-3.540112	2.728860	0.289133
Four-Tired Single Rear Axle	-3.439501	0.423747	1.846657
Eight-Tired Tandem Axle	-2.979479	-1.265144	2.007989
Twelve-Tired Tridem Axle	-2.740987	-1.873428	1.964442
Sixteen-Tired Quad Axle	-2.589482	-2.224981	1.923512
Twenty-Tired Quint Axle	-2.264324	-2.666882	1.937472
Twenty-four Tired Sextet Axle	-2.084883	-2.900445	1.913994

tridem were determined for comparison to various uneven load patterns. Figure 3 shows the results of the regression on all data without regard to load pattern. Table 2 summarizes the coefficients and regression statistics for Figure 3. The influence of structure upon the scatter of data as the result of uneven loading within the tridem was very significant, but structure was not nearly so influential for an uneven load distribution within a tandem. For 670 tandems, the accumulated adjusted EAL was 1.4 times that of an evenly distributed load. For 1,951 tridems, the accumulated adjusted EAL was 2.3 times that of evenly distributed loads.

FLOTATION VERSUS DUAL TIRES

In recent years, wide flotation tires have been utilized on steering axles and, more recently, to replace dual tires on rear axles. Ready-mix transit trucks that once had ten tires on three axles, or fourteen tires on four axles, now may have a total of six, or eight, tires, respectively, with all tires being the same size. To determine the effects of single flotation versus "standard" dual tires, the same pavement structures used previously were analyzed. The loads on each tire ranged from 5.5 kips (24.5 kN) to 9.5 kips (42.3 kN). The total load on the assembly was divided equally and applied to all flotation tires. The response was compared to the response having the same total load using standard dual tire arrangements on the same number of axles. The total work calculated by the Chevron N-layer computer program coupled with a fatigue relationship provided the number of equivalent 18-kip (80-kN) axleloads (EAL's). Damage factors, or load factors, were calculated for flotation tires on tandem and tridem groups. Figure 4 compares damage factors for the axle assemblies using single flotation or dual tires. There is a larger difference in damage factors between flotation tires and dual tires at lesser loads, and the damage factors approach equality at the higher loads. Contact areas for flotation tires at higher loads approach the total area of standard dual tires. Analyses have not been made for unequal load distributions on single flotation tires.

EFFECTS OF AXLE SPACING

To determine the sensitivity of damage factor to the distance between axles of a tandem group, a total load of 36 kips (160 kN) was divided equally among all eight tires -- 4.5 kips (40 kN) per tire. The appropriate relationship between axle spacing and an adjustment factor is defined as

$$\log(adj) = -1.589746 + 1.505263(\log(sp)) - 0.337357(\log(sp))^2 \qquad 3$$

in which adj = adjustment for axle spacing greater than 54 inches (1.37 m) and

sp = spacing between two axles of the tandem, inches.

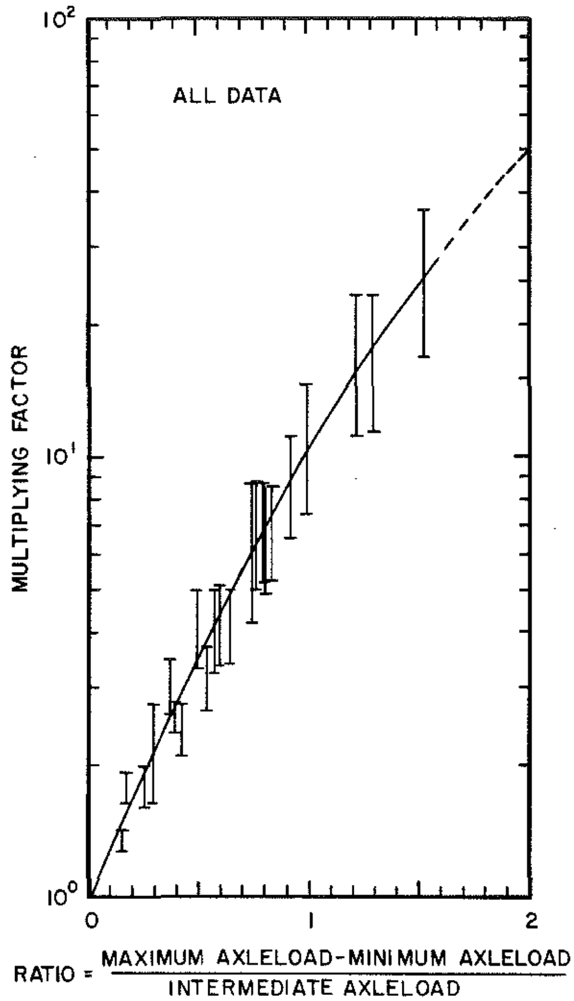

Figure 3. Multiplying Factor for Uneven Load Distribution on the Axles within the Tridem without Regard to Location of Maximum or Minimum Axleloads.

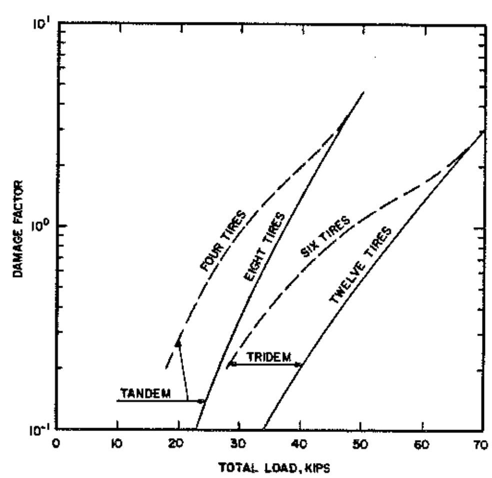

Figure 4. Load-Equivalency Relationships for Four-tired and Eight-tired Tandem Axles and for Six-tired and Twelve-tired Tridem Axles.

TABLE 2. COEFFICIENTS FROM REGRESSION ANALYSES OF UNEQUAL LOAD DISTRIBUTION ON INDIVIDUAL AXLES OF TRIDEM AXLE GROUP

$$\log(\text{Multiplying Factor}) = a + b(\text{Ratio}) + c(\text{Ratio})^2$$

in which Ratio = (M − L) / I

M = Maximum Axleload, kips,
I = Intermediate Axleload, kips,
L = Least Axleload, kips, and
a,b,c = coefficients

Load Pattern: 1. L,I,M 2. M,I,L 3. M,E,E 4. E,E,M	
Constant a	0.468782731
Coefficient b	1.093207072
Coefficient c	-0.1503124207
Standard Error of Estimate	0.073149
Correlation Coefficient, R	0.96024
F Ratio	1183.4
Sample Size	648
Load Pattern: 1. I,L,M 2. M,L,I 3. E,L,E	
Constant a	-0.1161216122
Coefficient b	1.507954095
Coefficient c	0.377814882
Standard Error of Estimate	0.069341
Correlation Coefficient, R	0.92765
F Ratio	326.9
Sample Number	343
Load Pattern: 1. L,M,I 2. I,M,L 3. E,M,E	
Constant a	-0.0235937584
Coefficient b	1.283412872
Coefficient c	-0.2187655038
Standard Error of Estimate	0.088165
Correlation Coefficient, R	0.92395
F Ratio	710.7
Sample Size	478
Load Pattern: 1. L,E,E 2. E,E,L	
Constant a	0.0004399421
Coefficient b	0.8053052125
Coefficient c	0.2363591702
Standard Error of Estimate	0.05634
Correlation Coefficient, R	0.96827
F Ratio	1037.4
Sample Size	282
Load Pattern: All Patterns Above	
Constant a	-0.198429071
Coefficient b	1.20191282
Coefficient c	-0.1746353238
Standard Error of Estimate	0.09792
Correlation Coefficient, R	0.9240
F Ratio	2085.4
Sample Size	1951

KINGPIN LOCATION

The kingpin location, the connection between a trailer and the tractor, may be varied by the trucker up to as much as 24 or 30 inches (610 or 762 mm) from its desirable location. Displacements of the kingpin by as much as 18 inches (457 mm) is not uncommon. Such a displacement may shift a portion of the trailer load to the steering axle where small increases in load are proportionately more damaging to the pavement as well as creating a safety problem by increasing the difficulty of steering.

In August 1978, 129 vehicles of the "332" classification (five-axle semi-trailer truck) were inspected and weighed at a scale on I 64 in Kentucky. Figure 5 shows that the front axleload generally increased as the kingpin assemble was located farther from the center of the tandem. The increase from 9 kips (40 kN) to 10.7 kips (47.6 kN) on the front axle causes the damage factor for that axle to increase from 0.2 to 0.4. However, a 1.7-kip (7.6-kN) increase of the tandem axleload of 34 kips (151.2 kN) causes an increase in the damage factor of only 0.18. Analysis indicates that simply moving the kingpin assembly back to the center of the tandem on the tractor will not increase the pavement life significantly. No adjustment factor for location of the kingpin is utilized because any shift in position is directly reflected in the axleloads.

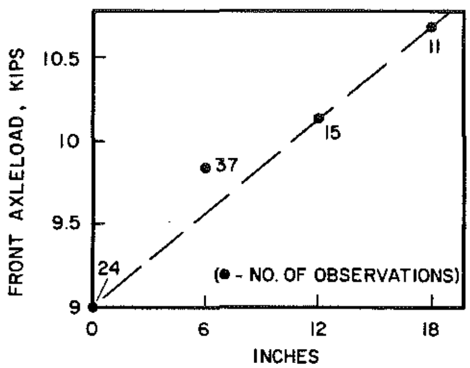

Figure 5. Front Axleload versus Position of Kingpin Assemble Relative to the Center of Tractor Tandem.

EFFECTS OF TIRE PRESSURES (4)

While investigating a premature pavement failure, a sample of the axleloads, tire contact lengths, tread widths, types of tire construction (radial or bias ply), tire pressures, and axle spacings were obtained for 14 trucks to help recreate the fatigue history. Loadometer data had been obtained during the summer of 1984 at the loadometer station located approximately one mile (1.6 km) south of the pavement then under study. Tire pressures also were measured only on the left outside tires of all axles on another 39 trucks. Figure 6 is a histogram summarizing tire pressure data in 5-psi (34-kPa) intervals. In summary, the following observations are made:

1. Seventy-four percent of all tires were radials.
2. Pressures in seven percent of all tires ranged between 120 and 129 psi (827 kPa and 889 kPa).
3. The average tire pressure for all tires was 102 psi (701 kPa).
4. The average tire pressure for all tires on the steering axle was 105 psi (726 kPa).
5. The average tire pressure for all tires on rear axles was 101.4 psi (699 kPa).
6. Pressures for radial tires:
   a. the average for all tires was 105 psi (723 kPa),
   b. the average for the steering axle was 108 psi (743 kPa), and
   c. the average for tires on rear axles was 104 psi (717 kPa).
7. Pressures for bias-ply tires:
   a. the average for all tires was 90 psi (617 kPa) and
   b. there was only 0.3-psi (2-kPa) difference in pressure between the steering and rear axle tires.
8. The average pressure in radial tires was 15.3 psi (105 kPa) higher than that for bias ply tires.
9. As much as 40 psi (276 kPa) differential was detected between tires within the same tandem group. Five flat tires were not included in this analysis.

At the AASHO Road Test, most tires were inflated to 75 psi (517 kPa), resulting in a contact pressure of 67.5 psi (465 kPa). Increased tire pressures decrease the length (and thus area) of the tire in contact with the pavement. The reduced area causes an increased punching effect within the pavement. As tire pressures increase, the punching effect will increase and may create a shearing failure surface different from the traditional form of a spiral curve. The Chevron N-layer computer program does not account for such punching-type failures.

The same structures used in the previous analyses were loaded using an 18-kip (80-kN) four-tired single axleload and analyzed by the Chevron N-layer computer program for a reference condition defined as a tire inflation pressure of 75 psi (517 kPa), which corresponded to a tire contact pressure of 67.5 psi (465 kPa) used at the AASHO Road Test. Tire pressures investigated in this analysis were 80 psi (552 kPa), 115 psi (793 kPa), 150 psi (1.03 MPa), and 200 psi (1.38 MPa). Work was calculated at the bottom of the asphaltic concrete layer and under the inside tire at the edge closest to the end of the axle, the location of maximum work determined from previous analyses.

All damage factors associated with loads and adjustment factors for variations in load distribution between axles and distance between axles of a tandem have been determined to be relatively insensitive to pavement thickness. However, Figure 7 illustrates that the magnitudes of adjustment factors for variations in tire pressures for four-tired single axles are dependent upon the thickness of the asphaltic concrete. Figures 8 and 9 present adjustment factors for variations in tire pressures on eight-tired tandem and twelve-tired tridem axle groups, respectively. In Figures 7 through 9, it was assumed that all tires were equally loaded. Substituting the terms "adjustment factor" for "damage factor" and "tire pressure" for "load", the form of the

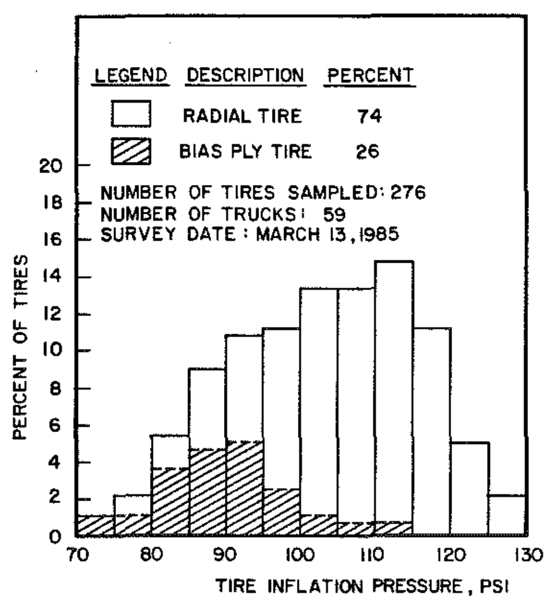

Figure 6. Histogram of Measured Tire Pressures.

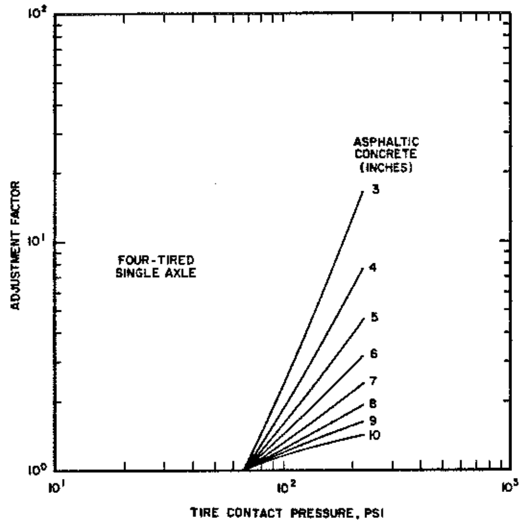

Figure 7. Adjustment Factor versus Tire Contact Pressure for Four-tired Single Axles.

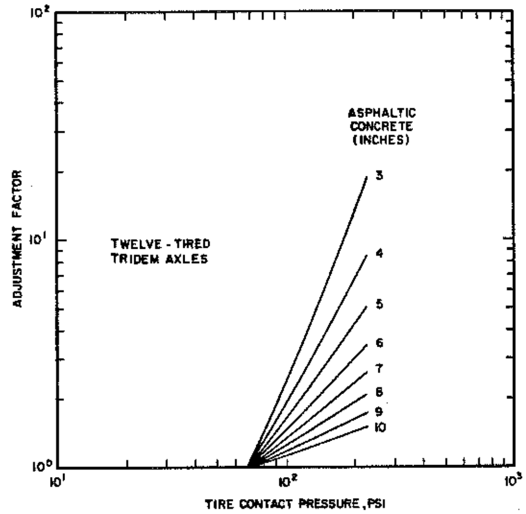

Figure 9. Adjustment Factor versus Tire Contact Pressure for Twelve-tired Tridem Axles.

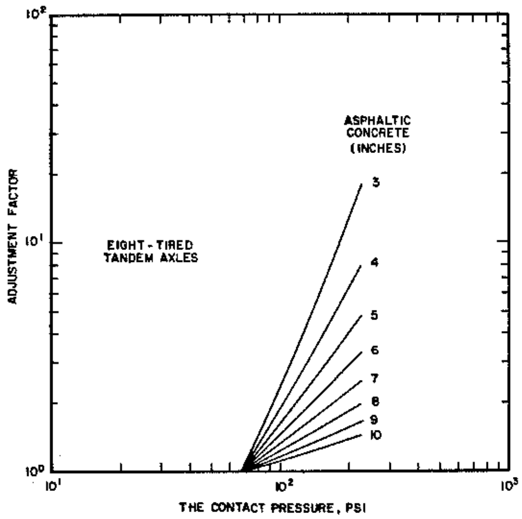

Figure 8. Adjustment Factor versus Tire Contact Pressure for Eight-tired Tandem Axles.

equation in Figure 2 describes the adjustment factor as a function of tire pressure for a constant thickness of asphaltic concrete. Values for the regression coefficients are given in Table 3.

Another analysis was made for axle groupings using flotation tires instead of dual tires. Figures 10 through 12 present adjustment factors as a function of tire pressures for single-, tandem-, and tridem-axle groups. Note that fatigue effects of tire-pressure variations for flotation tires are much more severe (as much as four to five times) as for the same pressure in groups using dual tires.

To illustrate the increased fatigue caused by increased tire pressures, loadometer data obtained during the summer of 1984 at a site on I 65 in Hardin County, Kentucky, were analyzed. The pavement 1 mile (1.6 km) north of the loadometer station consisted of 7 inches (178 mm) of asphaltic concrete over 16 inches (406 mm) of dense-graded aggregate base. For the steering axle, multiplying the inflation pressure by 0.9 (= 67.5 psi/75 psi) yields an approximate contact pressure of 95 psi (653 kPa). For all tires on rear axles, the average inflation pressure of 101 psi (699 kPa) was multiplied by 0.9 to obtain an approximate contact pressure of 91 psi (629 kPa). Adjustment factors are shown in Table 4.

Axleload data collected at the loadometer station were analyzed by vehicle classification to determine an average damage factor for each axle location and for the total vehicle. Table 5 contains four sets of average damage factors for the vehicle classifications at that loadometer station. The first set of factors were obtained using the AASHTO load equivalencies associated with a structural number of 4.0 and level of serviceability of 2.5. The remaining sets show the result of including more detailed data (additional adjustments for non-reference loading conditions) in determining the damage factors. Effects of the different sets of damage factors will be shown in an example problem. Average damage factors shown in Table 5 were obtained from data obtained at one site only, but probably are indicative of comparisons between vehicle classifications.

USING TRAFFIC DATA

Weigh-in-motion data provide the necessary ingredients to calculate the damage factor for each vehicle and the average for each vehicle classification. Changes in legal load limits, typical axleloadings, axle and tire arrangements, and use of particular vehicle types have resulted in increased damage factors. Knowledge of these changing trends provides the possibility for estimating EAL for both existing and future pavements with greater accuracy and confidence.

TABLE 3. REGRESSION COEFFICIENTS TO CALCULATE ADJUSTMENT FACTORS FOR VARYING TIRE PRESSURES AND AXLE CONFIGURATIONS FOR EQUALLY DISTRIBUTED TIRE LOADS

$$\log(\text{Factor}) = A + B \log(\text{TCP}) + C (\log(\text{TCP}))^2$$

in which TCP = Tire Contact Pressure

THICKNESS OF ASPHALTIC CONCRETE (inches)	COEFFICIENTS A	B	C
	TWO-TIRED SINGLE AXLE		
3	-11.423641	8.452615	-1.206807
4	-9.718723	7.272744	-1.071370
5	-8.667064	6.604668	-1.020443
6	-7.983404	6.219065	-1.013936
7	-7.528589	6.005482	-1.033063
8	-7.225865	5.903743	-1.067872
9	-7.029159	5.878171	-1.112632
10	-6.909049	5.906263	-1.163835
	FOUR-TIRED TANDEM AXLE		
3	-11.983535	8.850933	-1.257276
4	-10.133166	7.527803	-1.086909
5	-9.191001	6.946769	-1.050864
6	-8.721212	6.741902	-1.079290
7	-8.540266	6.763541	-1.145226
8	-8.543689	6.926599	-1.233377
9	-8.670125	7.181627	-1.335045
10	-8.881250	7.498079	-1.444985
	SIX-TIRED TRIDEM AXLE		
3	-12.227565	9.069919	-1.304090
4	-10.347085	7.708593	-1.121828
5	-9.423848	7.141287	-1.087605
6	-9.016720	6.994653	-1.129134
7	-8.913110	7.093011	-1.213003
8	-9.009383	7.342882	-1.321764
9	-9.230684	7.690169	-1.445523
10	-9.539068	8.101609	-1.578329
	FOUR-TIRED SINGLE AXLE		
3	-2.464465	0.576804	0.420942
4	-1.962926	0.591450	0.263080
5	-1.637979	0.612273	0.154626
6	-1.414034	0.635424	0.075089
7	-1.253849	0.659304	0.014209
8	-1.136684	0.683179	-0.033811
9	-1.049978	0.706696	-0.072534
10	-0.985633	0.729684	-0.104286
	EIGHT-TIRED TANDEM AXLE		
3	-2.573477	0.647141	0.414958
4	-2.221248	0.803333	0.224419
5	-1.889261	0.818996	0.116696
6	-1.579889	0.763381	0.054667
7	-1.291573	0.668360	0.020454
8	-1.022015	0.550498	0.004322
9	-0.768984	0.419143	0.000498
10	-0.530517	-0.279885	0.005342
	TWELVE-TIRED TRIDEM AXLE		
3	-2.640784	0.686070	0.413835
4	-2.224371	0.777724	0.239410
5	-1.829865	0.730261	0.147497
6	-1.461152	0.614593	0.100533
7	-1.116870	0.462852	0.080565
8	-0.794540	0.291453	0.077889
9	-0.491654	0.109482	0.086793
10	-0.205964	-0.077749	0.103706

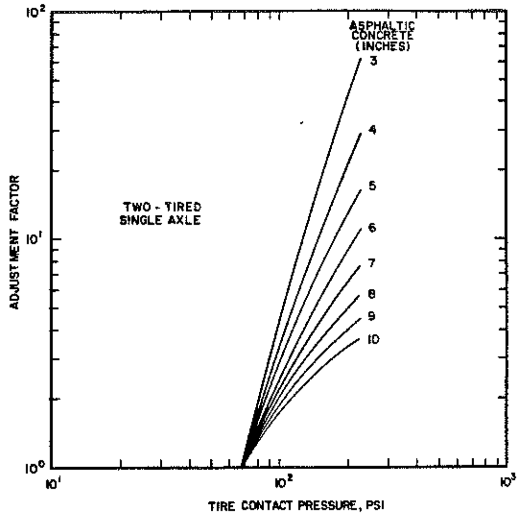

Figure 10. Adjustment Factor versus Tire Contact Pressure for Two-tired Single Axles.

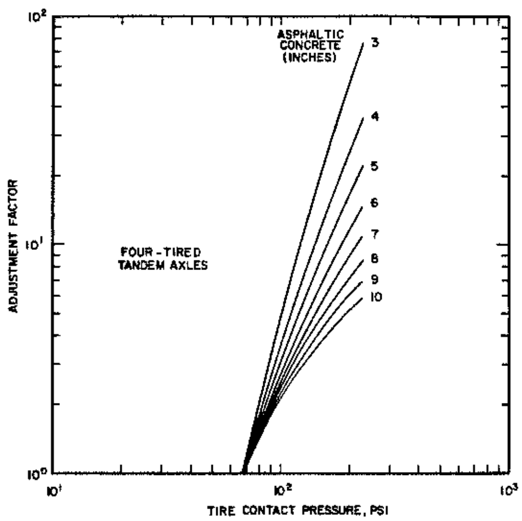

Figure 11. Adjustment Factor versus Tire Contact Pressure for Four-tired Tandem Axles.

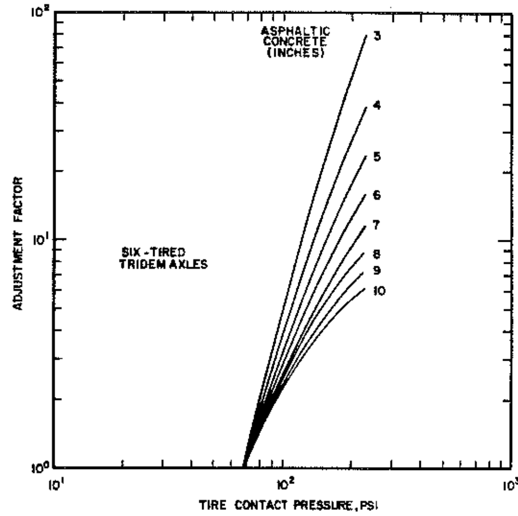

Figure 12. Adjustment Factor versus Tire Contact Pressure for Six-tired Tridem Axles.

Trends in vehicle usage may be evaluated from weigh-in-motion data without the need for manual vehicle classification counts. To estimate the rate of consumption of the remaining pavement life, trends of vehicle-type usage, magnitudes of loads, and accumulation rates of pavement fatigue must be known or projected.

Analyses of 1984 Kentucky loadometer data yielded the first definitive data for "double-bottom" trucks (tractor plus semi-trailer plus full trailer). This combination in Kentucky utilizes two short trailers that together are approximately equal to the length of the traditional semi-trailer. Axleload data for each double-bottom truck were used to calculate the gross load and the total damage factor for that vehicle. A search of the data listing was made for a "332" vehicle (five-axle semi-trailer truck) having the same gross load. The damage factors for each vehicle type were summed and an average obtained as shown in Table 6. For the 33 pairs, the average damage factor for the "double-bottoms" was 1.74 times greater than the average for the "332" vehicles.

CASE HISTORY

As referred to earlier, it was necessary to recreate an estimated accumulated fatigue history for a particular pavement that had

TABLE 4. ADJUSTMENT FACTORS FOR TIRE CONTACT PRESSURES

AXLE LOCATION	AVERAGE CONTACT PRESSURE, PSI	ADJUSTMENT FACTOR*
Steering	94.7	2.0202
Four-Tired Single	91.3	1.2393
Eight-Tired Tandem	91.3	1.2508
Twelve-Tired Tridem	91.3	1.2590

*Thickness of Asphaltic Concrete = 7 inches (178 mm)
Tire Contact Pressure = 0.9 (Inflation Pressure)
1 psi = 6,894.8 Pa

TABLE 5. COMPARISON OF AVERAGE DAMAGE FACTORS FOR VARIOUS VEHICLE CLASSIFICATIONS

VEHICLE CODE	AASHTO DAMAGE FACTOR	KENTUCKY METHODS DAMAGE FACTORS A	B	C
CARS*	0.0020	0.0050	0.0050	0.0050
22	0.1981	0.2082	0.2082	0.3212
23	0.1174	0.3410	0.4668	0.8432
24**	0.1185	0.3410	0.4668	0.8443
321	0.3989	0.4501	0.4501	0.7226
322	0.4372	0.4673	0.4852	0.7584
332	1.1663	0.7735	0.9609	1.4272
333	0.8594	0.7126	0.7401	1.2481
5212	2.0302	1.8785	1.8785	2.5553
6312	1.2779	1.1330	1.1984	1.6292

Method A Includes No Adjustments.
Method B Includes Adjustments for Uneven Load Distribution and Axle Spacing Only.
Method C Includes Method B Plus Adjustments for Tire Contact Pressure.
*Cars Plus Others not Specifically Included.
**No Data for This Category on Loadometer Tape -- Assumed to be the Same as for "23" in These Analyses.

Vehicle Code
"22" = Two-axle truck, six tires
"23" = Three-axle single-frame truck, 10 tires
"24" = Four-axle single-frame truck, 14 tires
"321" = Three-axle semi-trailer truck having three single axles
"322" = Four-axle semi-trailer truck having two single axles and one tandem axle group
"332" = Five-axle semi-trailer truck having one single and two tandem axle groups
"337" = Five-axle semi-trailer truck having one single axle and one tandem axle group on the tractor and a tandem group having spread axles on the trailer
"333" = Six-axle semi-trailer truck having one single axle and one tandem axle group on the tractor and one tridem axle group
"5212" = Five-axle combination consisting of one tractor, with two single axles and one semi-trailer with one single axle followed by a full trailer with two single axles
"6312" = Six-axle combination consisting of a tractor with a single axle and one tandem axle group and one semi-trailer with one single axle followed by a full trailer with two single axles

failed prematurely. Available data included

1. vehicle volumes by hour for each day during the life of the pavement obtained by an automatic traffic recorder,
2. quarterly manual vehicle classification counts, and
3. loadometer studies for input to the annual W-4 tables.

An estimate of traffic volume by vehicle classification was obtained using ATR and manual classification counts. Loadometer data were analyzed several ways. The simplest procedure involved estimating the load equivalency for each vehicle. All variations in load distribution amongst axles within a group and axle spacings were ignored. Under these assumptions, the data were subjected to analyses using both the Kentucky and AASHTO damage factor relationships. The average damage factor for each vehicle was accumulated for the respective vehicle classification and an average equivalency value obtained for each classification as shown in Table 5. Accumulating the product of vehicle volume and respective average damage factor produced the total accumulated 18-kip (80-kN) equivalent axleloads shown in Table 7.

A second analysis of the loadometer data included adjustments to account for uneven axleloads within the axle group (tandem or tridem) and the effects of increased spacing over 54 inches (1.3 m) within a tandem group. As before, a damage factor for each vehicle was calculated and accumulated within its classification. An average damage factor was calculated for each vehicle classification after all vehicles had been investigated. The total 18-kip (80-kN) equivalent axleloads were obtained for each vehicle classification as the product of the respective

TABLE 6. FATIGUE CALCULATIONS FOR "DOUBLE-BOTTOM" TRUCKS COMPARED TO FIVE-AXLE SEMI-TRAILER TRUCKS

VEHICLE NUMBER	DOUBLE-BOTTOM TRUCK GROSS LOAD, KIPS	DAMAGE FACTORS AASHTO	DAMAGE FACTORS '81 KY	FIVE-AXLE SEMI-TRAILER GROSS LOAD, KIPS	DAMAGE FACTORS AASHTO	DAMAGE FACTORS '81 KY
1	74.8	3.4524	3.9200	74.9	1.9314	2.0968
2	52.1	0.6943	0.7397	52.1	0.4523	0.4993
3	73.0	3.2530	3.7474	73.0	1.8180	1.5378
4	63.2	1.5343	1.5191	63.0	1.0347	1.0059
5	66.3	1.7517	1.5849	66.3	1.3235	1.2880
6	68.9	2.6632	2.8002	69.0	1.4038	1.3980
7	78.3	3.5905	3.7275	78.3	2.4021	2.1119
8	63.6	1.4319	1.3033	63.6	1.0089	0.7173
9	57.4	0.9610	0.9143	57.5	0.8545	0.7702
10	57.7	0.9271	0.8896	57.9	0.7252	1.0050
11	53.2	0.6758	0.6937	53.3	0.4926	0.4887
12	52.4	0.6801	0.6784	52.5	0.4836	0.4519
13	69.2	2.1202	1.9713	69.1	1.5433	1.2892
14	58.4	1.0750	1.0466	58.4	0.9884	0.8808
15	57.7	0.9921	0.9791	57.9	0.7252	1.0050
16	55.6	0.8821	0.8989	55.8	0.6143	1.0534
17	66.7	2.0937	2.0425	66.8	1.3998	1.0909
18	53.5	0.7387	0.7563	53.5	0.5680	0.4455
19	81.0	3.7338	3.9503	80.7	2.5560	2.3570
20	51.8	0.7001	0.7624	51.9	0.4436	0.5629
21	75.7	3.1153	3.1272	75.6	2.0570	1.5125
22	63.1	1.8607	1.9355	63.0	1.0167	1.1788
23	71.9	2.8771	3.1460	71.9	1.6849	1.4980
24	58.3	0.9939	0.9480	58.4	0.9884	0.8808
25	51.3	0.6021	0.6220	51.1	0.4128	0.4123
26	75.2	3.2352	3.5540	76.5	2.1554	1.7250
27	76.4	3.0525	3.1171	76.5	2.1554	1.7250
28	66.8	2.9656	3.4525	66.9	1.2514	1.2067
29	70.5	2.5926	2.7276	70.5	1.5037	1.2829
30	31.0	0.1035	0.2127	31.3	0.0837	0.1948
31	52.2	0.9870	0.7933	52.2	0.4500	0.4228
32	43.3	0.3810	0.4604	43.2	0.2701	0.3463
33	77.0	3.4345	3.6330	77.1	2.1418	1.5747
Average		1.8228	1.8961		1.1762	1.0885
AASHTO		1.8228 / 1.1762 = 1.5497				
'81 KY		1.8961 / 1.0885 = 1.7419				

classification volume and average load equivalency value.

The third analysis adjusted the damage factors obtained by the second analysis for increased tire contact pressure. Adjustments were made using the factors listed in Table 4.

AASHTO damage factors assume that the effects of the steering axle are taken into account through the factors for the rear axles. Those damage factors also assume that all axles in a given assembly are equally loaded. This assumption was valid at the AASHO Road Test because of the careful placement of loads on the trailers. Current data indicate that equal load distributions on the axles within the same group are seldom the case.

Some have used the AASHTO "single-axle damage factor relationship" for determining effects of loads on steering axles. Even though this is not the correct procedure, AASHTO damage factors for single axleloads were applied to the steering axles of the above case history. Table 7 contains the comparison of the four methods of calculating pavement fatigue.

To determine a reasonable estimate of the total fatigue damage caused by the front axle, one method of analysis combined the damage factors for the steering axle listed in Table 8 with the appropriate vehicle volumes from Table 7. The total accumulated fatigue for the steering axle (Method C in Table 8) was 340,613 18-kip (80-kN) EAL of the total of 845,175 18-kip (80-kN) EAL. Thus, the estimated fatigue associated with the steering axle was 40 percent of the total fatigue caused by all axles. The comparable value using the AASHTO method was 52,976 18-kip (80-kN) EAL, which was eight percent of the total of 662,522 EAL. Thus, a greatly reduced fatigue estimate is obtained.

TABLE 7. FATIGUE HISTORY DATA FOR CASE HISTORY

VEHICLE CODE	VOLUME	AASHTO EAL	EAL BY KENTUCKY METHODS A	B	C
CARS*	1,659,946	3,319.9	8,299.7	8,299.7	8,299.7
22	82,737	15,331.2	17,225.8	17,225.8	17,225.8
23	8,684	2,056.4	2,961.3	4,053.7	7,322.7
24	4,284	1,014.4	1,460.8	1,999.7	3,716.9
321	15,220	6,071.3	6,850.6	6,850.6	10,997.6
322	22,830	9,981.3	10,668.5	11,077.1	17,493.5
332	506,630	579,584.7	391,878.3	486,820.8	717,981.8
337	19	27.9	18.4	23.5	33.8
333	2,962	2,559.2	2,110.8	2,192.2	3,696.8
5212	22,490	45,659.2	42,247.4	42,247.4	57,469.7
6312	575	734.8	651.4	668.3	936.7
Total	2,687,154	662,522.1	484,373.0	581,458.8	845,175.0

Kentucky EAL / AASHTO EAL = 845,175.0 / 662,522.1 = 1.2757

Kentucky Method:

A = Includes No Adjustments.

B = Includes Adjustments for Uneven Load Distribution and Axle Spacing Only.

C = Includes Method B Plus Adjustments for Tire Contact Pressure on 7-inch (178 mm) Thickness of Asphaltic Concrete.

*Cars Plus Others not Specifically Included.

SUMMARY

All adjustment factors presented are based on the analyses of a limited number of structures and should be used with caution. The accuracy of these analyses is not in question, but the range of structures investigated was limited. They are intended to indicate the trend, shape, and sensitivity of various inter-relationships and their relative magnitudes. Modifications may be necessary after additional analyses of pavement structures. Kentucky traffic may differ from that in other locations, both in types of vehicles in the traffic stream and the types and direction that cargo is being transported.

Damage factor relationships for axle and tire configurations are presented. Adjustment factors are provided to account for variations in load distributions within axle groups, distances between axles of a tandem, and variations in tire pressure for both dual and flotation tire configurations. Properly accounting for accumulated fatigue of a pavement requires a reasonable measure of traffic volume, proportions of vehicle styles (classifications) within the traffic stream, dates of service, estimates of the average damage factor for each classification, and estimates of the tire contact pressures.

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TABLE 8. COMPARISON OF DAMAGE FACTORS

VEHICLE CODE	AXLE TYPE NUMBER	AASHTO DAMAGE FACTOR	KENTUCKY METHODS DAMAGE FACTORS A	B	C
CARS*		0.0020	0.0050	0.0050	0.0050
22	1	0.0171	0.0810	0.0810	0.0810
	2	0.1810	0.1272	0.1272	0.1272
	Total	0.1981	0.2082	0.2082	0.2082
23	1	0.1130	0.3371	0.3371	0.6810
	3	0.0044	0.0039	0.1297	0.1622
	Total	0.1174	0.3410	0.4668	0.8432
24	1	0.1130	0.3371	0.3371	0.6810
	4	0.0055	0.0039	0.1297	0.1633
	Total	0.1185	0.3410	0.4668	0.8443
321	1	0.0621	0.2110	0.2110	0.4263
	2	0.2334	0.1675	0.1675	0.2076
	2	0.1034	0.0716	0.0716	0.0887
	Total	0.3989	0.4501	0.4501	0.7226
322	1	0.0581	0.2005	0.2005	0.4051
	2	0.3242	0.2424	0.2424	0.3004
	3	0.0549	0.0244	0.0423	0.0529
	Total	0.4372	0.4673	0.4852	0.7584
332	1	0.0893	0.2798	0.2798	0.5653
	3	0.5598	0.2648	0.3327	0.4161
	3	0.4949	0.2289	0.3484	0.4358
	Total	1.1440	0.7735	0.9609	1.4172
333	1	0.1482	0.4190	0.4190	0.8465
	3	0.4227	0.1906	0.1744	0.2181
	4	0.2885	0.1030	0.1467	0.1835
	Total	0.8594	0.7126	0.7401	1.2481
5212	1	0.0939	0.2911	0.2911	0.5881
	2	0.6889	0.6017	0.6017	0.7457
	2	0.5750	0.4799	0.4799	0.5947
	2	0.3583	0.2721	0.2721	0.3372
	2	0.3141	0.2337	0.2337	0.2896
	Total	2.0302	1.8785	1.8785	2.5553
6312	1	0.0515	0.1830	0.1830	0.3697
	3	0.1540	0.0642	0.0936	0.1171
	2	0.6198	0.5268	0.5628	0.6975
	2	0.0097	0.0096	0.0096	0.0119
	2	0.4429	0.3494	0.3494	0.4330
	Total	1.2779	1.1330	1.1984	1.6292

Axle Type Number:
- 1 = Two-Tired Steering Axle
- 2 = Four-Tired Single Axle
- 3 = Eight-Tired Tandem Axle
- 4 = Twelve-Tired Tridem Axle

Kentucky Method:
- A = Includes No Adjustments.
- B = Includes Adjustments for Uneven Load Distribution and Axle Spacing Only.
- C = Includes Method B Plus Adjustments for Tire Contact Pressure.

*Cars Plus Others not Specifically Included.